Earth Orbiter 1 - Wideband Advanced Recorder and Processor (WARP)

Terry Smith
NASA Goddard Space Flight Center
Greenbelt, MD 20771

John Kessler
Litton Amecom
College Park, MD 20740

ABSTRACT

An advanced on-board spacecraft data system component is presented. The component is computer-based and provides science data acquisition, processing, storage, and base-band transmission functions. Specifically, the component is a very high rate solid state recorder, serving as a pathfinder for achieving the data handling requirements of next-generation hyperspectral imaging missions.

INTRODUCTION

As spacecraft instruments generate data at ever increasing rates, space systems must find ways to handle that data, and transmit it to the ground stations. This challenge is especially evident on earth-imaging spacecraft employing multispectral and hyperspectral detectors. The LANDSAT 7 instrument data rate is 150 Mbps. The EO-1 instrument data rate is over 500 Mbps. The next generation LANDSAT is expected to have an instrument data rate of several Gigabits per second. Earth Orbiter 1 (EO-1) is a stepping stone to the next generation LANDSAT mission. A key goal of EO-1 is to pioneer and flight-prove technologies that will make that mission feasible. This paper describes the EO-1 on-board science data handling system, and recommends architectures and technologies for future systems.

FLIGHT DATA SYSTEM TECHNOLOGY TRENDS

While instrument data rates have evolved several orders of magnitude over the last decade, the data system architectures and technologies required to handle those data rates have lagged behind. The projection over the next decade is for that gap to get even wider.

Data Acquisition Interfaces

Data acquisition interfaces between instruments and bulk data storage units have long relied on parallel implementations of the EIA RS-422 standard data interface. Each RS-422 differential pair can transfer data at a maximum rate of about 10 Mbps over a 5 meter cable. The primary disadvantages of parallel RS-422 data interfaces are very heavy and bulky cables, high power, large circuit board area, and impractical redundancy. LANDSAT 7 uses serial Emitter Coupled Logic (ECL) coaxial cable data interfaces. Each serial interface transfers data at a maximum rate of 75 Mbps. The primary disadvantages of the ECL interface are very high power, EMI, and voltage conversions. Alternatively, the Earth Observing System (EOS) AM and PM spacecraft use the Advanced Micro Devices (AMD) Taxi ® data interface. The AMD Taxichips ® are serial communication devices that transfer data at a maximum rate of 125 Mbps (military version). However, the latest versions are not radiation tolerant (latch-up susceptible), and the older versions are no longer available. In development is the spaceborne Fiber Optic Data Bus (FODB), standard IEEE-P1393. The FODB is a redundant serial communication bus that transfers data at a maximum rate of 1 Gbps. However, technical hurdles remain, and developmental funding is inconsistent.

On-Board Science Data Processing

On-board science data processing has been largely absent from remote sensing missions. The future use of on-board science data processing will depend on mission objectives, instrument data rate, downlink technology, and cost constraints. There are two primary architectural options to implement science data processing. The first is real-time and hardware-based. The second is post-acquisition and software-based, possibly with a hardware accelerator. Hardware-based processing typically requires a custom implementation and hence is expensive. Software-based processing is less expensive and more flexible, but requires a fast general-purpose hardware platform on which to run. While commercial microprocessor speeds have increased steadily to the 400 MHz range, their radiation hardened (latch-up and single-event upset immune) counterparts have lagged behind in the tens of MHz range. Configurable array processors have the potential to accelerate the processing, however significant development remains to make this technology viable for space applications.

Bulk Data Storage
Data storage technology has undergone the most change of the data handling functions. Over the past decade, the implementation of this function has gone from tape recorders to solid state recorders (SSRs). Data storage quantity has gone from less than 1 Gbit to 400 Gbits. Solid state recorders offer the functional benefits of random access memory and dynamic rate buffering. They also offer a reliability advantage over electro-mechanical technology. The first SSRs were implemented with Static Random Access Memory (SRAM). More recent SSRs are implemented with Dynamic Random Access Memory (DRAM). Compared to SRAM, DRAM is denser and less costly, but consumes more power. Density is also dependent on whether 2-dimensional or 3-dimensional packaging is used. 3-dimensional packaging (multi-chip stacks) is denser, but more costly. Density is further dependent on the percentage of overhead functions in the system. Overhead functions include power conversion, data input, data output, and data processing. Current SSRs exhibiting 25% overhead, using ten-high plastic encapsulated module stacks, and 16 Mbit DRAM are achieving a density of about 12 Mbits per cubic centimeter. The same SSR using 64 Mbit DRAM die can achieve about three times more density, or 36 Mbits per cubic cm. 256 Mbit DRAM may soon replace 64 Mbit DRAM, pending their radiation tolerance.

Downlink and Base-Band Data Transmission
Downlink architectures and technologies are the key data flow bottleneck for remote sensing missions. Polar low-earth orbiting spacecraft have very limited periodic opportunities to downlink data. Even with very high latitude ground stations, these spacecraft only have about 10 minutes out of each 100 minute orbit to downlink data. Early LANDSAT missions used a several-Mbps S-Band Downlink. The LANDSAT 7 spacecraft uses an extravagant tri-downlink architecture that has three separately gimbaled X-Band antennas. Each X-Band downlink carries 150 Mbps, yielding a total bandwidth of 450 Mbps. EO-1 has a 105 Mbps X-band downlink implemented with an electrically steered phased array antenna. Next generation RF downlink systems will probably use the Ka band, and will achieve about 350 Mbps per link. At this data rate, the base-band transmission interfaces to the I and Q channels of a QPSK modulator will have to be upgraded from the current Emitter Coupled Logic (ECL) implementations, to Gallium Arsenide (GAs) or an equivalent technology.

Technology Trend Conclusions
The conclusion of this technology trend evaluation is that instrument data rates are increasing much faster than data acquisition interface technology and downlink technology. Science data processing technology is still in its infancy. Data storage technology is currently increasing rapidly, however the future trend may be inhibited by the radiation tolerance of these ever-shrinking commercial devices. Also, the amount of data storage for missions requiring raw, global, high-resolution data will still be very large, very heavy, and very expensive. If flight qualified disk-based data storage technology becomes mature, perhaps it will become viable for these missions. However, numerous obstacles remain, including data rate performance, reliability, radiation tolerance, and induced torque.

EO-1 FLIGHT DATA SYSTEM

The EO-1 Mission will be launched on a Delta 7320 from Vandenberg Air Force Base on or about December 1, 1999. After deployment from the third stage of the Delta, EO-1 will fly in a 705 km circular, sun-synchronous orbit at a 98.7 degree inclination. This orbit allows EO-1 to match within one minute, the Landsat-7 orbit and collect identical images for later comparison on the ground.

Figure 1 shows the science data handling section of the EO-1 Flight Data System.

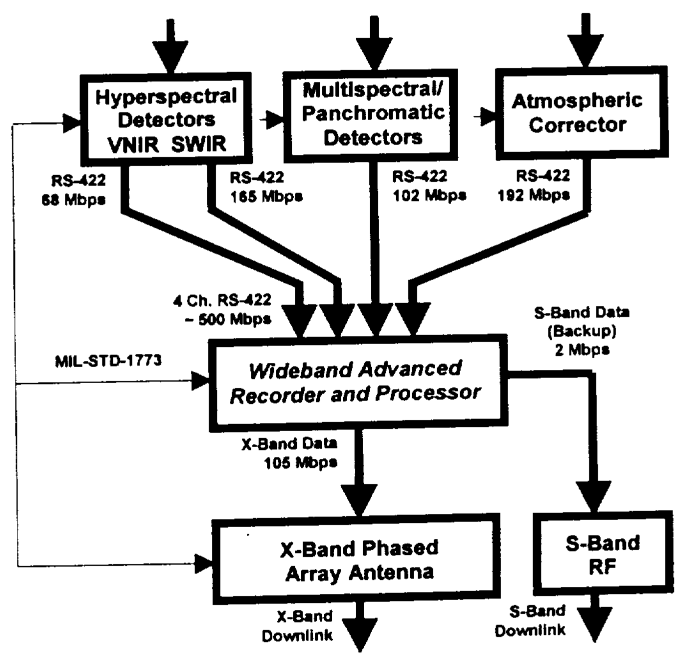

Figure 1. EO-1 Flight Data System Architecture.

The EO-1 Flight Data System is controlled and monitored through a MIL-STD-1773 Data Bus from an on-board Command and Data Handling (C&DH) Unit (not shown). When commanded by the C&DH Unit, the instruments acquire ground images (scenes), and transfer those scenes at high rates to the WARP. The WARP stores the scenes as files in bulk memory. When in contact with the ground station, the spacecraft automatically transmits the recorded scenes to the ground station via an X-Band Downlink or an S-Band Backup Downlink.

Instrument Descriptions

Three revolutionary land imaging instruments on EO-1 collect multispectral and hyperspectral scenes over the course of its mission. The first instrument is the Advanced Land Imager (ALI). The ALI contains multispectral and panchromatic (MS/PAN) band detectors. The second instrument is the Hyperion. The Hyperion contains two grating imaging spectrometer (GIS) hyperspectral detectors: A Short Wave infrared (SWIR) band, and a Visible Near infrared (VNIR) band. The third instrument is the Atmospheric Corrector. The Atmospheric Corrector data is used to compensate for distortions in the acquired science data. The combined continuous data rate from these three instruments is about 500 Mbps. The original baseline mission also featured wedge imaging spectrometer (WIS) hyperspectral detectors that were subsequently deleted. The combined continuous instrument data rate of the original baseline mission was 760 Mbps.

RF System Description

The primary downlink is through an X-Band Phased Array Antenna at 105 Mbps. The downlink has QPSK modulation with separate files being transmitted on the I and Q channels. The transmission is balanced at 52.5 Mbps per channel. EO-1 has a backup downlink through an S-Band Omni Antenna at 2 Mbps.

THE EO-1 WARP

The EO-1 spacecraft component that handles the science data is the Wideband Advanced Recorder and Processor (WARP). Figures 2 and 3 show the WARP in box-level integration and test.

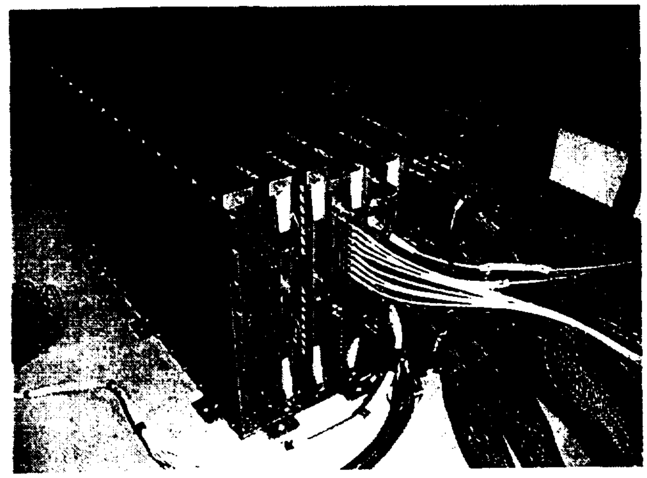

Figure 2. Primary Boards in Box-Level Integration and Test.

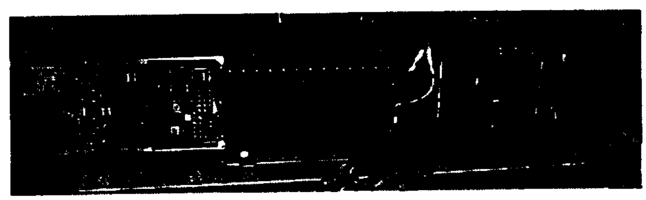

Figure 3. Primary Boards in Box-Level Integration and Test. The left board is attached through a connector on the rear of the WARP Backplane. The right board is attached using an extender board. The rear Backplane connector allows testing of an exposed board without the added parasitic inductance and capacitance of an extender board. Boards that are not as sensitive to the parasitic effects can be tested on the extender board. This technique allows two boards to be probed simultaneously during integration and test.

Key WARP Specifications

Data Storage:	48 Gbits
Record Rate:	>1 Gbps Burst 900 Mbps Continuous
Playback Rate:	105 Mbps X-Band Built-in RF Exciter
Data Processing:	Post-Record Capability
Size:	25 x 39 x 37 cm
Mass:	23 kg
Power:	45 W orb average, 110 W Peak
Thermal:	0-40 °C minimum operating
Mission Life:	1 year minimum
Radiation:	15 krad total dose, LET 35 MeV

WARP Architecture and Operation

Figure 4 shows the WARP Hardware Architecture.

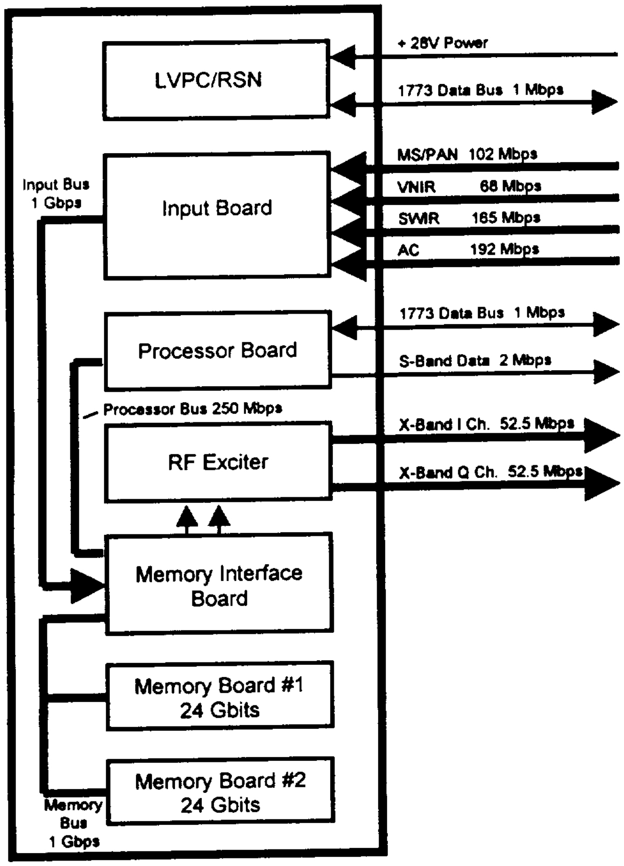

Figure 4. WARP Hardware Architecture

The Low Voltage Power Converter / Remote Services Node (LVPC/RSN) is a dual function board. The LVPC converts the + 28 V Primary Spacecraft Power into the required secondary voltages. The RSN is a microcontroller-based function. It receives commands across the MIL-STD-1773 Data Bus to power on and off certain boards within the WARP, depending on the operational mode. This reduces the WARP's orbital average power. There are four operational modes: Low Power, Data Record, Data Hold and Processing, and X-Band Data Playback. The RSN also acquires housekeeping telemetry within the WARP such as thermistor data, voltage levels, and current levels. The telemetry is transferred back across the MIL-STD-1773 Data Bus to the C&DH Unit.

Data Record Mode

Prior to the initiation of the Data Record Mode, the Processor Board sends commands to the Input Board that select which channels will be recorded. The Processor Board also sends commands to the Memory Interface Board that define where the scene data will be stored in the Memory. Upon receiving the appropriate MIL-STD-1773 command, all the instruments transmit pixel data in bursts across their respective parallel RS-422 interfaces. Each Parallel RS-422 Interface consists of 32 data lines and 1 clock line. The Input Board receives the data, filters out appropriate channels and "dead zone" data, rate buffers each channel, and multiplexes each channel into one data stream. It then transmits the data across the 1 Gbps Input Bus to the Memory Interface Board.

The Memory Interface Board receives the input data, and breaks the data stream up into fixed length code blocks. It then appends a short Reed-Solomon Error Detection and Correction (EDAC) field to the end of each code block, interleaves the data, and transmits the data stream across the 1 Gbps Memory Data Bus to the Memory Boards. The Reed-Solomon encoding allows radiation induced single event upset bit errors to be corrected on playback. The data interleaving, which spreads code blocks across memory chips, allows data corrections even if entire memory chips fail.

The Memory Boards receive the data stream, generate detailed address locations, and store the data. Each scene of each instrument detector channel is stored in a separate file. Each Memory Board has 24 Gbits of data, organized as six 4 Gbit Arrays. Figure 5 shows a picture of the Memory Board.

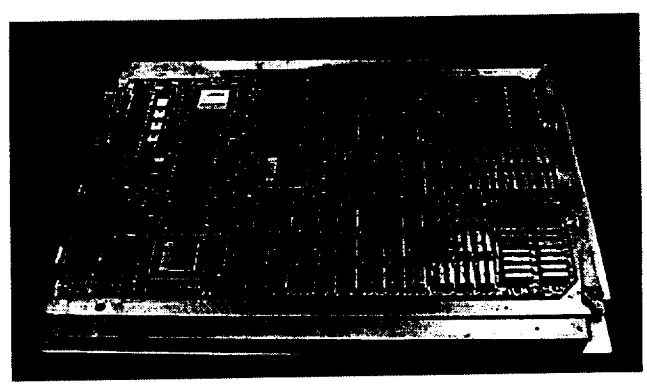

Figure 5. WARP Memory Board. The WARP Memory Board is dual sided. It is implemented with 8-high stacks of 16 Mbit DRAM PEMs. Six Field Programmable Gate Arrays (FPGAs) are used. Due to the very wide data busses that are necessary to handle the 1 Gbps data rate, a significant amount of non-DRAM logic devices are required. To meet the memory density requirements within the fixed printed wiring board real estate, the non-DRAM logic is implemented with wire bond chip-on-board technology.

In addition to science data recording, the WARP also records full resolution instrument housekeeping data across the MIL-STD-1773 Data Bus. The housekeeping data is stored in a memory buffer on the Processor Board until after the science data record is complete. The Processor Board then transmits the housekeeping data across the 250 Mbps Processor Bus to the Memory Interface Board, which then performs the same operations as it did with the science data stream.

Data Hold and Processing Mode

To maintain the data in memory, the Memory Boards perform DRAM refresh periodically until the data is transmitted to the ground. Once the data is stored, the WARP has the optional capability of post-processing the data. The Processor Board contains a 32 bit, 12 MHz Reduced Instruction Set (RISC) Micoprocessor called the Mongoose 5. The software uses the VxWorks/Tornado Operating System and C programming language. The Processor Board also has a rice algorithm lossless data compression chip capable of up to a 1.8:1 compression ratio, depending on the image entropy. To post-process the data, the Processor Board retrieves the desired data from the Memory Boards, and re-formats the data from the detector focal plane readout order, to band-sequential order. Once the data is in band-sequential order, virtually any processing function can be implemented in software. Examples of post-processing functions include thumbnail imaging, cloud detection, radiometric calibration, and data compression. The baseline mission of the WARP does not include post-processing software due to schedule constraints, however this software may be developed and uploaded later during extended mission operations. Once the data is processed, it is returned to the Memory Boards.

X-Band Data Playback Mode

The WARP performs X-Band data playback by transferring files from the Memory Boards to the Memory Interface Board. The Memory Interface Board de-interleaves the data, performs error detection and correction on the data using the short Reed-Solomon Decoders, formats the data in accordance with the CCSDS AOS Data Recommendation, appends long Reed-Solomon error detection and correction coding, and transmits the data to the RF Exciter. Two data streams are transmitted to the RF Exciter, an I channel and a Q channel. The data streams are partitioned such that files are transmitted separately down the I and Q channels.

WARP Technologies

The following technologies were critical to achieve the WARP requirements:

1) Mongoose 5, 32 bit, 12 MHz Microprocessor

2) Essential Services Node Multi-chip Module

3) Chip-On-Board Packaging Technology

4) EDAC5HS High Speed (1 Gbps) Reed-Solomon error detection and correction chips

5) Universal Source Encoder for Space (USES) chip implementation of the rice data compression algorithm.

6) Actel 14100 Field Programmable Gate Arrays (FPGAs)

7) 16 Mbit DRAM, 8 High Stack PEMs

TECHNOLOGY TRANSFER TO INDUSTRY

The above technologies are all available to industry. Goddard Space Flight Center developed the first 5 technologies under the Cross-Enterprise Technology Development Program. Goddard Space Flight Center also developed the WARP architecture and designs. Portions of the WARP design have certain restrictions. The Amecom division of Litton Industries has entered into a Space Act Agreement with Goddard Space Flight Center to share in the cost and the hands-on development of the WARP. As a result of the Space Act Agreement, Litton Amecom has certain exclusive rights to commercialize the WARP designs for a period of two years. Amecom's commercial interest in the WARP technology, and the next generation of this recorder technology, is in its ability to ingest the extremely high data rates of a hyperspectral instrument and the scalable architecture of the system. The memory capacity of the WARP is easily expandable to the Tera-Bit range.

FUTURE TECHNOLOGY PRIORITIES

Several top-level goals for future LANDSAT-type missions will dominate and influence technology development priorities. The first goal is that future NASA spacecraft will be an order of magnitude smaller and lighter than current versions. They will also have smaller budgets. The second goal is that the science community will continue to demand global coverage, full spatial coverage, wide spectral coverage, and full pixel resolution raw science data. While the EO-1 mission will provide on-orbit demonstration and validation of several spacecraft technologies to enable this transition, other key technologies must also be developed to achieve these next generation goals.

The following technologies will be essential to meeting the next generation LANDSAT goals:

Fiber Optic Data Bus
- 128 Node ring architecture
- 1 Gbps data rate
- Asynch. Transfer Mode (ATM) based network
- Parallel implementation demonstrated
- Available in 1999
- NASA/GSFC and DoD

High Performance Data Compression.
- 20:1 data compression ratio
- Nearly lossless algorithm
- 500 Mbps max input rate
- 2-chip set
- Available in 2000
- GSFC and University of New Mexico

High Density, High Speed, Rad Hard FPGAs
- *NASA/GSFC and DoD*

256 Mbit Rad Hard DRAM

High Rate Point-To-Point Serial Data Interface
- SSR to RF System Downlink Channel

KA Band or Optical Downlink
- 350 Mbps or greater data rate

8 Phase Shift Keying (8PSK) Downlink

100 MIP Processors

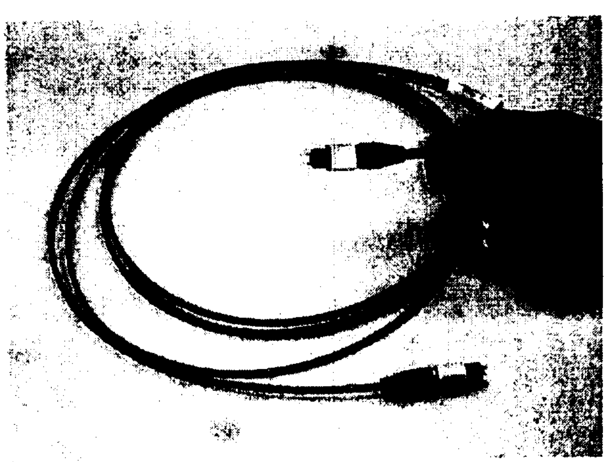

Figure 6. 1 Gbps Parallel FODB Ribbon Cable.

SUMMARY

Several critical conclusions can made regarding the flight data systems for next generation LANDSAT missions:

1) If the science community wants global coverage, full spatial coverage, wide spectral coverage, and full pixel resolution raw science data, then the most practical solution is high-performance data compression technologies that are not 100% lossless.

2) The technologies identified in this paper must be developed independent from flight programs. These technologies require long-term independent research and development (IR&D) modes of development, and cannot be developed as part of a short-cycle flight project.

3) The flight data system that is necessary to handle the extremely high data rates and volume requires significant development time. It should be considered part of the instrument, not part of the spacecraft. As such, its development should begin early when the instrument development begins. Otherwise, it will severely impact the mission development schedule.

ACKNOWLEDGMENTS

The entire WARP Team from Goddard Space Flight Center, Swales Aerospace, Litton Amecom, and Daedalian Systems Corporation is acknowledged for their extraordinary efforts and long hours spent in bringing this technology to fruition.

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